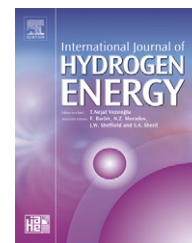


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Exergy analysis of the woody biomass Stirling engine and PEM-FC combined system with exhaust heat reforming

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ABSTRACT

The woody biomass Stirling engine (WB-SEG) is an external combustion engine that outputs high-temperature exhaust gases. It is necessary to improve the exergy efficiency of WB-SEG from the viewpoint of energy cascade utilization. So, a combined system that uses the exhaust heat of WB-SEG for the steam reforming of city gas and that supplies the produced reformed gas to a proton exchange membrane fuel cell (PEM-FC) is proposed. The energy flow and the exergy flow were analyzed for each WB-SEG, PEM-FC, and WB-SEG/PEM-FC combined system. Exhaust heat recovery to preheat fuel and combustion air was investigated in each system. As a result, (a) improvement of the heat exchange performance of the woody biomass combustion gas and engine is observed, (b) reduction in difference in the reaction temperature of each unit, and (c) removal of rapid temperature change of reformed gas are required in order to reduce exergy loss of the system. The exergy efficiency of the WB-SEG/PEM-FC combined system is superior to EM-FC.

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1. Introduction

Utilization of woody biomass is discussed from the view of the environmental problem [1–3]. In Japan, the utilization as a woody biomass fuel of thinned wood or building scrap wood is investigated. Authors are evaluating the test Stirling engine (WB-SEG) that burns these woody biomasses directly [4]. The theoretical thermal efficiency of a Stirling cycle is higher than a Diesel cycle at heat for the same input temperature level. However, in actual WB-SEG, the heat transmission control between combustion gas and the engine is difficult and heat supply temperature are limited [4]. In the experiment, the heat released down stream of the engine represents at least 60% in total loss [4]. As far as exergy efficiency of an energy system is concerned, loss in the combustor is large [5]. Therefore, the high-temperature heat released when woody biomass needs to be used effectively for utilization of

WB-SEG. However, when such release is used for space heating and hot water supply, it is not effective from the view of energy cascade utilization. So, in this study, the combined system of WB-SEG and PEM-FC is proposed. There are very few reports of research regarding the WB-SEG and PEM-FC combined system [6]. The study on the complex system of a fuel cell and an engine is uncivilizedness, and the example of the system especially using a Stirling cycle is few. The burning exhaust heat of WB-SEG is used for the heat source of a steam generator (vaporizer), and a reforming unit for steam reforming of city gas in this system. The exhaust heat of each unit can be used for preheating of fuel and combustion air in this system. However, low-temperature exhaust heat, such as engine-cooling water of WB-SEG and cell stack exhaust heat of PEM-FC, is used for space heating and hot water supply. There are many methods to optimize the leading of different efficiency level. In the

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Nomenclature		Subscript	
A_r	surface area of the combustion chamber, m^2	a	exhaust gas of the combustion chamber
C_a	mean specific heat of exhaust gas, $J/(kg K)$	br	combustion gas
C_w	specific heat of engine-cooling-water, $J/(kg K)$	c	CO oxidation unit
$\dot{E}$	power, W	ca	air supplied to the combustor unit
E_s	generating end output, W	cb	burning
e	exergy, W	ce	reformed gas of the CO oxidation equipment unit
K	the rate of overall heat transfer, $W/(m^2 K)$	ch	chemical
L_b	calorific value of the woody biomass, J/g	cr	CO oxidation heat
$\dot{q}_a$	exhaust gas quantity of heat, W	en	energy
$\dot{q}_b$	the amount of combustion heat of the woody biomass, W	ex	exergy
q_r	the amount of heat release from the combustion chamber surface, W	f	cell stack
q_w	engine-cooling-water quantity of heat, W	fa	air supplied to the cell stack
R	power load factor, %	fe	exhaust gas of the cell stack
r_{ce}	utilization rate of anode gas, %	fr	cell stack heating valve
r_{fa}	utilization rate of cathode gas, %	ga	air supplied to the combustor unit
Δt_a	difference of exhaust gas temperature and room temperature, K	gc	city-gas supplied to the combustor unit
Δt_r	difference of combustion-chamber temperature and room temperature, K	gv	city-gas supplied to the vaporizer unit
Δt_w	difference of engine-cooling-water and room temperature, K	r	reformer unit
V_a	exhaust gas flow rate, m^3/s	ra	reforming heat
V_f	supply of the woody biomass, g/s	rb	combustion gas
V_w	engine-cooling-water flow rate, g/s	re	reformed gas of the reformer unit
$\dot{H}$	heat, W	rm	heat release of the combustion chamber
h	enthalpy, J/mol	rw	water supplied to the vaporizer unit
i	exergy loss, W	s	shifter unit
L_b	lower calorific value of woody biomass, J/kg	sa	shifting heat
L_{CH_4}	lower calorific value of city-gas, J/kg	sc	cell stack
$\dot{m}$	molar flow rate, mol/s	se	reformed gas of the shifter unit
$\dot{q}$	heat quantity, W	si	output to the Stirling engine
$\dot{q}_{lhv}$	lower calorific value, J/mol	sys	system
T	temperature, K	tc	thermomechanical
Greek letters		v	vaporizer unit
η	efficiency	va	amount of heat of vaporization
ρ_a	mean density of emission	ve	reformed gas of the vaporizer unit
ρ_w	density of engine-cooling water	vo	exhaust heat of the vaporizer unit
		w	cooling-water of the Stirling engine
		wb	woody biomass
		0	standard reference

WB-SEG/PEM-FC combined system, because PEM-FC is operated using the exhaust heat of WB-SEG, exergy efficiency should improve. Therefore, in this study, the energy flow and the exergy flow are investigated in both of WB-SEG, PEM-FC, and the WB-SEG/PEM-FC combined system including preheating of fuel and combustion air.

2. System configuration

2.1. Stirling engine generator

Fig. 1(a) is the block diagram of WB-SEG. Woody biomass fuel (chips) and combustion air are supplied to the combustor. A heat exchanger is introduced and this is exchangeable for the

heat of the exhaust gas. The heat generated in the combustor is supplied to the engine heat exchanger. As exhaust heat, there is exhaust gas from burning and engine-cooling water. The heat of the engine-cooling water is supplied to a heat storage tank, and can be supplied to the demand side with a time shift. On the other hand, the combustion gas can select preheating of the biomass fuel and the combustion air, or supply to the heat storage tank. As shown in Fig. 1(b), engine power is transmitted to the power generator using a belt. The power outputted with the power generator is converted into a regular frequency by the inverter, and supplies stable voltage power and frequency to the grid. The output characteristics of WB-SEG shown in Fig. 1(c) are introduced into this analysis. These output characteristics were taken by examining an engine of the specification shown in Fig. 1(b). The heat of each

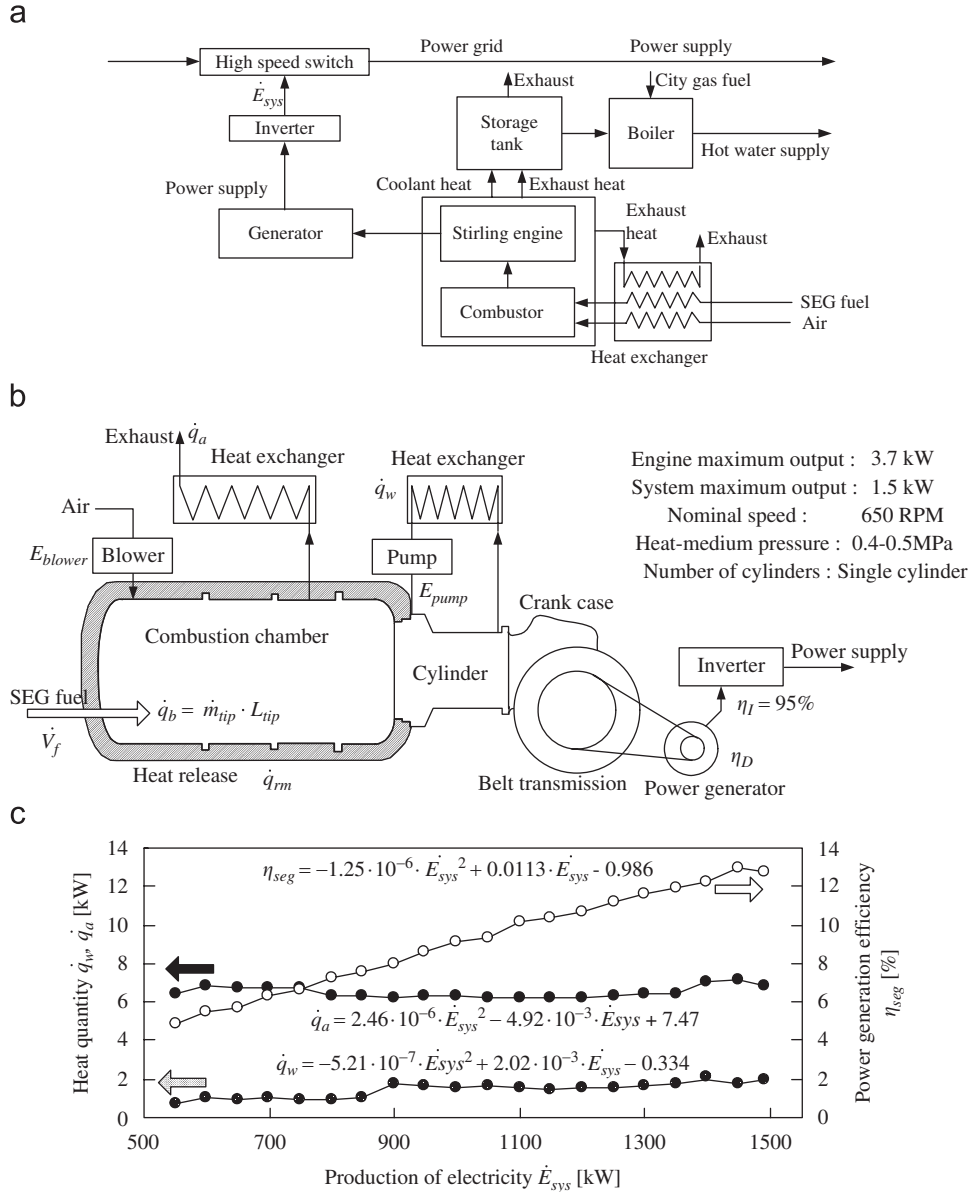


Fig. 1 – Stirling engine (WB-SEG) system. (a) Block diagram of Stirling engine generator (WB-SEG). (b) Test Stirling engine. (c) Result of energy output and power generation efficiency.

test WB-SEG was calculated using the following equations. Eq. (1) is the heat of the woody biomass fuel supplied to the engine. Eqs. (2) and (3) are the heat of the engine-cooling water and combustion gas, respectively. Eq. (4) is the heat discharge of the combustor.

$$\dot{q}_b = L_b \cdot \dot{V}_f, \quad (1)$$

$$\dot{q}_w = \rho_w \cdot C_w \cdot \Delta t_w \cdot \dot{V}_w, \quad (2)$$

$$\dot{q}_a = \rho_a \cdot C_a \cdot \Delta t_a \cdot \dot{V}_a, \quad (3)$$

$$\dot{q}_{rm} = K \cdot A_{rm} \cdot \Delta t_{rm}. \quad (4)$$

2.2. PEM-FC with a city gas reformer

2.2.1. Reformed gas system

Fig. 2(a) is the block diagram of PEM-FC with a city gas reformer. The composition of city gas is considered to be CH_4 in this analysis. Fig. 2(b) shows the reaction temperature of each unit of the reforming system and the gas concentration. City gas and combustion air are supplied to the combustor. Heat is supplied to the vaporizer and the reforming unit using the combustion gas of the combustor. The city gas and water for reforming are supplied to the vaporizer. In the reforming unit, there is H_2 , CO , and the steam occurring by the steam reforming of city gas. In the shifter unit, CO_2 and H_2 are generated from CO and steam. Some CO contained in the reformed gas is reduced by 10ppm or less by CO oxidation

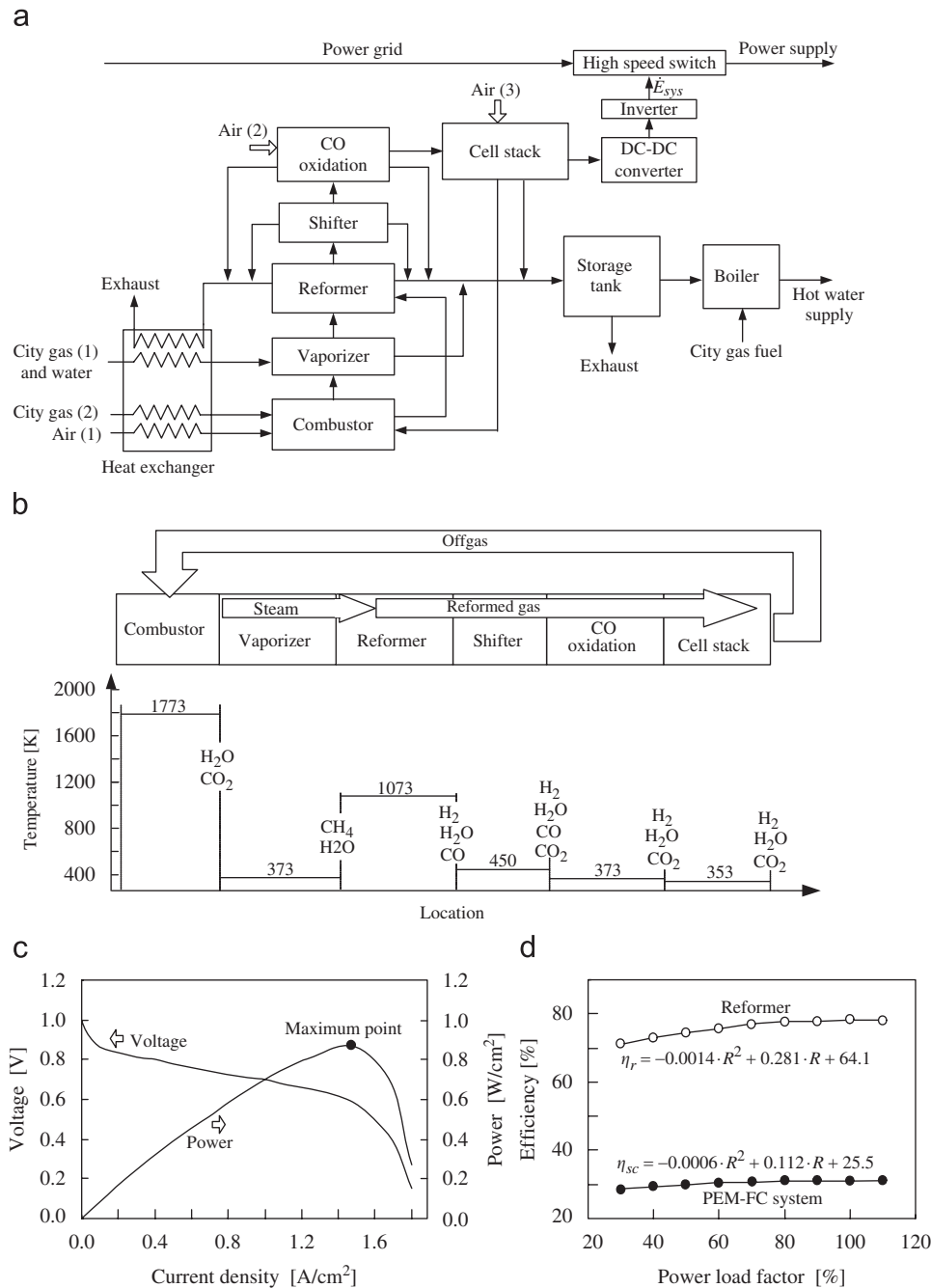


Fig. 2 – PEM-FC system. (a) Block diagram of PEM-FC with city-gas reformer. (b) Operation temperature of PEM-FC with reformer system. (c) Output characteristics of test cell stack. (d) Reformer efficiency and PEM-FC power generation efficiency.

reaction. This reformed gas is supplied to the anode of the cell stack. Among H_2 in the reformed gas supplied to the fuel cell, utilization rate r_{ce} is used for power generation. H_2 that is not used for power generation is supplied to the combustor, and is used for vaporization of water and the heat source of the reforming reaction.

2.2.2. Heat system

Exhaust heat is outputted from the vaporizer, the reforming unit, the shifter unit, the CO oxidation unit, and the cell stack. The high-temperature exhaust heat of the reforming unit, the shifter unit, and the CO oxidation unit is used for

preheating the fuel (CH_4 for burning and CH_4 for reforming), the water for reforming, and the combustion air. Whether the exhaust heat of the reforming unit, the shifter unit, and CO oxidation unit is used for preheating of the fuels, etc., or whether a heat storage tank is supplied can be selected. In fact, the distribution rate of the exhaust heat of preheating and thermal storage can be determined arbitrarily. However, in this paper, all the high-temperature exhaust heat is used for preheating, or all of it is stored in the heat storage tank. On the other hand, the exhaust heat of the vaporizer and the cell stack is always supplied to the heat storage tank.

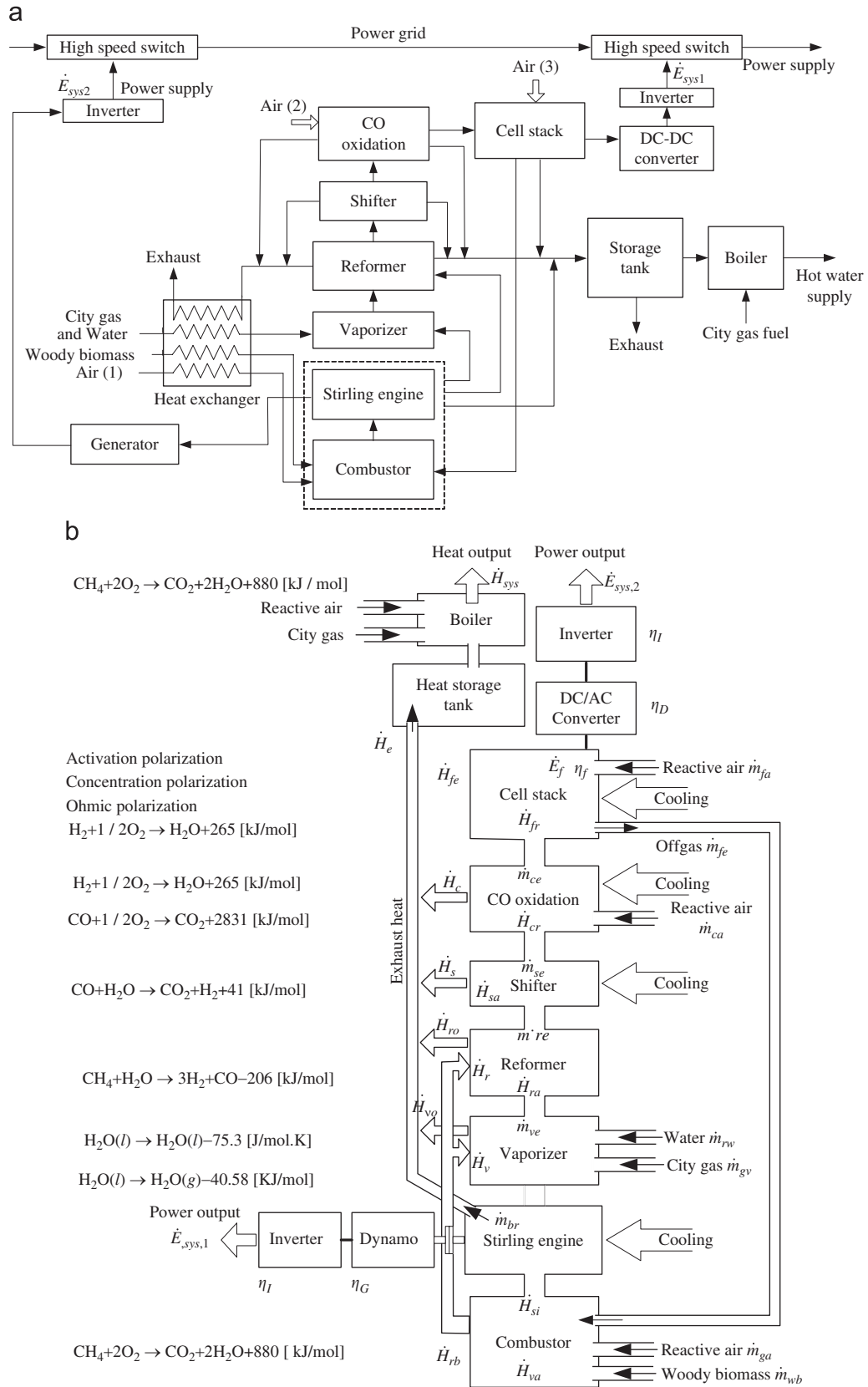


Fig. 3 – WB-SEG/PEM-FC combined system. (a) Block diagram of WB-SEG/PEM-FC combined system. (b) Chemical reaction and efficiency.

2.2.3. Output characteristics of the cell stack

Fig. 2(c) shows the output characteristics taken from a single cell experiment [7,8]. The single cell shown in Fig. 2(c) is built up, and the cell stack is composed. The number of cells of the cell stack decides that the generation efficiency of the maximum output point becomes the maximum. Fig. 2(d) shows the relation of the load factor and efficiency of the city gas reformer and PEM-FC to the city gas reformer [7–9]. The reformer efficiency and generating efficiency of the PEM-FC system were calculated using Eqs. (5) and (6), respectively.

$$\eta_r = \dot{q}_{\text{lhv},\text{H}_2} / ((\dot{m}_{\text{gc}} + \dot{m}_{\text{gv}}) \cdot L_{\text{CH}_4}), \quad (5)$$

$$\eta_{\text{sc}} = \dot{E}_s / ((\dot{m}_{\text{gc}} + \dot{m}_{\text{gv}}) \cdot L_{\text{CH}_4}). \quad (6)$$

2.3. WB-SEG/PEM-FC combined system

2.3.1. Block diagram

Fig. 3(a) is a block diagram of the combined system of WB-SEG and PEM-FC. Moreover, the chemical reaction and efficiency of each unit are shown in Fig. 3(b). Woody biomass and combustion air are supplied to the combustor unit. Moreover, city gas and water are supplied to the vaporizer unit. The combustion gas of the woody biomass is first given to the Stirling engine, and the exhaust heat is supplied to the vaporizer unit and the reforming unit. The exhaust heat of the reforming unit, the shifter unit, and the CO oxidation unit can select supplying preheating of the biomass fuel, combustion air, CH₄ for reforming and water, or storing in the heat storage tank. The power of the engine generator and the fuel cell is converted into alternating current power of constant frequency, and is supplied to the power grid.

2.3.2. Chemical reaction and efficiency

The chemical reaction, the efficiency, and the molar flow rate of each unit of the WB-SEG/PEM-FC combined system are shown in Fig. 3(a). In the next section, the energy flow and the exergy flow are calculated from the input–output and efficiency of each unit.

3. Analysis method

3.1. Energy flow of the WB-SEG/PEM-FC combined system

The conditions used for analysis of the system are shown in Table 1. Analysis of the energy flow and the exergy flow is calculated under standard conditions (25 °C, 0.1 MPa). A lower calorific value is used for fuel heat. Eqs. (7)–(12) are the energy balance equations of each unit. h in each equation expresses enthalpy. $\dot{H}$ and $\dot{E}$ express heat and power, respectively. The left-hand side of each equation expresses power input, and the right-hand side expresses output.

Combustor unit:

$$\dot{m}_{\text{wb}} \cdot h_{\text{wb}} + \dot{m}_{\text{ga}} \cdot h_{\text{ga}} + \dot{m}_{\text{fe}} \cdot h_{\text{fe}} + \dot{H}_{\text{cb}} = \dot{m}_{\text{br}} \cdot h_{\text{br}} + \dot{H}_{\text{rb}} + \dot{H}_{\text{si}}. \quad (7)$$

Vaporizer unit:

$$\dot{m}_{\text{gv}} \cdot h_{\text{gv}} + \dot{m}_{\text{rw}} \cdot h_{\text{rw}} - \dot{H}_{\text{va}} + \dot{H}_{\text{v}} = \dot{m}_{\text{ve}} \cdot h_{\text{ve}} + \dot{H}_{\text{vo}}. \quad (8)$$

Table 1 – Analysis parameters

Common conditions	
Standard condition	25 °C (293 K), 0.1 MPa
DC–DC converter efficiency	95%
Inverter efficiency	95%
WB-SEG	
Power output of generating end	1.5 kW
Generator efficiency	90%
Combustor efficiency	85%
Air–fuel ratio of combustor	1.2–2.0
PEM-FC	
Power output of generating end	1.5 kW
Anode fuel utilization rate	70%
Cathode fuel utilization rate	40%
CO oxidation efficiency	97%
Combustion loss of H ₂ in oxidation unit	97%
Mole ratio of water to CH ₄	1.2

Reformer unit:

$$\dot{m}_{\text{ve}} \cdot h_{\text{ve}} - \dot{H}_{\text{ra}} + \dot{H}_{\text{r}} = \dot{m}_{\text{re}} \cdot h_{\text{re}} + \dot{H}_{\text{ro}}. \quad (9)$$

Shifter unit:

$$\dot{m}_{\text{re}} \cdot h_{\text{re}} + \dot{H}_{\text{sa}} = \dot{m}_{\text{se}} \cdot h_{\text{se}} + \dot{H}_{\text{s}}. \quad (10)$$

CO oxidation equipment unit:

$$\dot{m}_{\text{se}} \cdot h_{\text{se}} + \dot{m}_{\text{ca}} \cdot h_{\text{ca}} + \dot{H}_{\text{cr}} = \dot{m}_{\text{ce}} \cdot h_{\text{ce}} + \dot{H}_{\text{c}}. \quad (11)$$

Cell stack:

$$\dot{m}_{\text{ce}} \cdot h_{\text{ce}} + \dot{m}_{\text{fa}} \cdot h_{\text{fa}} + \dot{H}_{\text{fr}} = \dot{m}_{\text{fe}} \cdot h_{\text{fe}} + \dot{H}_{\text{fe}} + \eta_{\text{f}} \cdot \dot{E}_{\text{f}}. \quad (12)$$

Eq. (13) is the energy balance equation of the system. The left-hand side expresses power input terms, and the right-hand side expresses output terms. n and m in this equation are the number of units inputted and outputted, respectively. $\dot{H}_{\text{sys}}$ and $\dot{E}_{\text{sys}}$ of the right-hand side express the heat output and the power output of the system, respectively. Moreover, the generation efficiency of the system is calculated using Eq. (14). $q_{\text{lhv},\text{wb}}$ in this equation expresses the calorific value of the woody biomass.

$$\sum_{i=1}^n \dot{m}_{\text{in},i} \cdot h_{\text{in},i} = \sum_{j=1}^m \dot{m}_{\text{out},j} \cdot h_{\text{out},j} + \dot{H}_{\text{sys}} + \dot{E}_{\text{sys},1} + \dot{E}_{\text{sys},2} + \dot{H}_{\text{loss}} + \dot{E}_{\text{loss}}, \quad (13)$$

$$\eta_{\text{en},\text{sys}} = \frac{\dot{E}_{\text{sys},1} + \dot{E}_{\text{sys},2}}{\dot{m}_{\text{wb}} \cdot q_{\text{lhv},\text{wb}} + \dot{m}_{\text{gv}} \cdot q_{\text{lhv},\text{CH}_4}} \times 100 \ (%). \quad (14)$$

3.2. Exergy flow of the WB-SEG/PEM-FC combined system

The quantity of exergy is the sum of chemical exergy, thermomechanical exergy, kinetic exergy, and potential exergy. In this paper, kinetic exergy and potential exergy are not calculated, because they are very small values compared with chemical exergy (e_{ch}) and thermomechanical exergy (e_{tc}).

So, the value of each exergy is calculated by

$$e = e_{ch} + e_{tc}. \quad (15)$$

The exergy balance of the system is calculated by Eq. (16). e_{in} and e_{out} show the input and output of exergy, and e_{diss} and e_{dest} show exergy dissipation and exergy destruction, respectively.

$$e_{in} = e_{out} + e_{diss} + e_{dest}. \quad (16)$$

Eq. (17) is an exergy balance expression. The left-hand side is the input term, and there are substance inputs and heat inputs. The right-hand side is the output term. The first term of the right-hand side expresses the output of substance, the second term expresses the heat output, the third term expresses the power output, and the last term expresses exergy loss.

$$\sum_{i=1}^n \dot{m}_{in,i} \cdot e_{in,i} + (1 - T_0/T_{in}) \cdot \dot{H}_{in} = \sum_{j=1}^m \dot{m}_{out,j} \cdot e_{out,j} + (1 - T_0/T_{out}) \cdot \dot{H}_{out} + \dot{E} + \dot{I}. \quad (17)$$

Eqs. (18)–(23) are exergy balance expressions of each unit. The left-hand side of each equation expresses input, and the right-hand side expresses output.

Combustor unit:

$$\dot{m}_{wb} \cdot e_{wb} + \dot{m}_{ga} \cdot e_{ga} + \dot{m}_{fe} \cdot e_{fe} = (1 - T_0/T_{rb}) \cdot \dot{H}_{rb} + (1 - T_0/T_{si}) \cdot \dot{H}_{si} + \dot{I}_{si}. \quad (18)$$

Vaporizer unit:

$$\dot{m}_{gv} \cdot e_{gv} + \dot{m}_{rw} \cdot e_{rw} + (1 - T_0/T_v) \cdot \dot{H}_v = \dot{m}_{ve} \cdot e_{ve} + \dot{I}_v. \quad (19)$$

Reformer unit:

$$\dot{m}_{ve} \cdot e_{ve} + (1 - T_0/T_r) \cdot \dot{H}_r = \dot{m}_{re} \cdot e_{re} + (1 - T_0/T_{ro}) \cdot \dot{H}_{ro} + \dot{I}_r. \quad (20)$$

Shifter unit:

$$\dot{m}_{re} \cdot e_{re} = \dot{m}_{se} \cdot e_{se} + (1 - T_0/T_s) \cdot \dot{H}_s + \dot{I}_s. \quad (21)$$

CO oxidation equipment unit:

$$\dot{m}_{se} \cdot e_{se} + \dot{m}_{ca} \cdot e_{ca} = \dot{m}_{ce} \cdot e_{ce} + (1 - T_0/T_c) \cdot \dot{H}_c + \dot{I}_c. \quad (22)$$

Cell stack:

$$r_{ce} \cdot \dot{m}_{ce} \cdot e_{ce} + r_{fa} \cdot \dot{m}_{fa} \cdot e_{fa} = \dot{m}_{fe} \cdot e_{fe} + (1 - T_0/T_{fe}) \cdot \dot{H}_{fe} + \eta_f \cdot \dot{E}_f + \dot{I}_f. \quad (23)$$

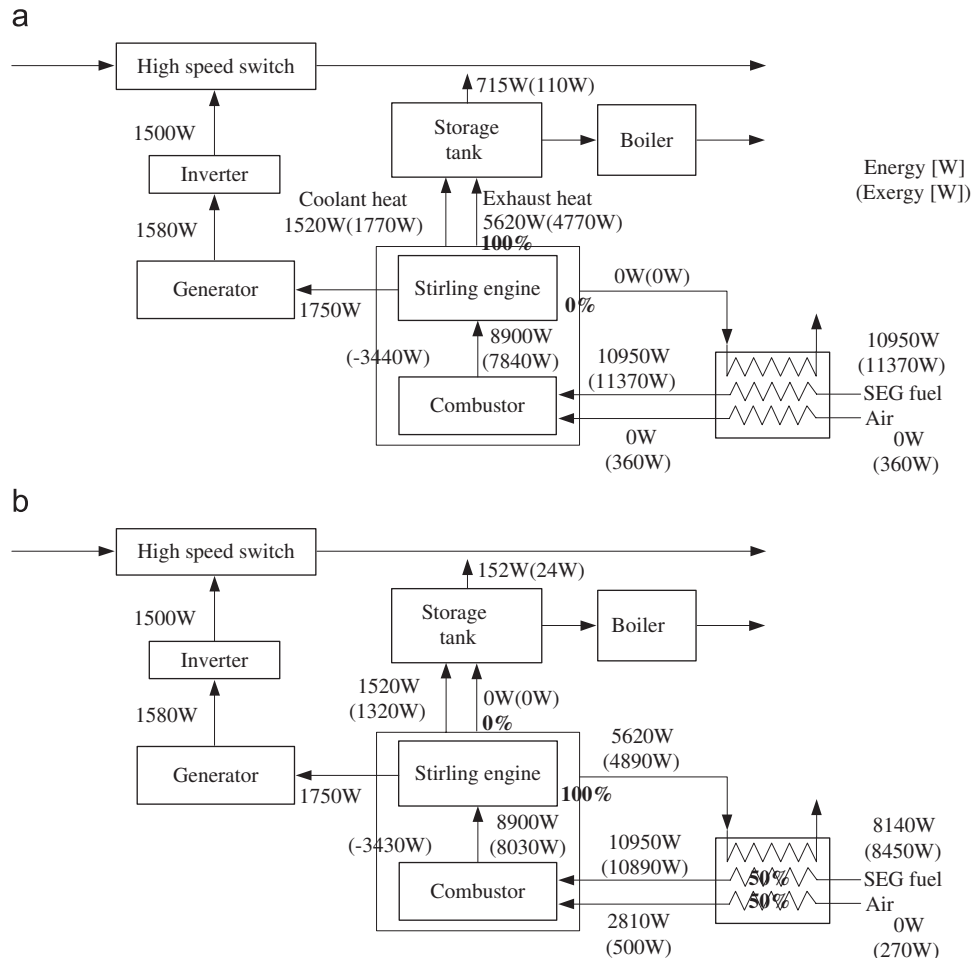


Fig. 4 – Energy flow and exergy flow of WB-SEG. (a) Fuel-preheating-less system. (b) Fuel-preheating system.

The exergy efficiency of the system is calculated using

$$\eta_{\text{ex,sys}} = \frac{e_{\text{out}}}{e_{\text{in}}} = \frac{\dot{E}_{\text{sys},1} + \dot{E}_{\text{sys},2}}{\dot{m}_{\text{wb}} \cdot e_{\text{wb}} + \dot{m}_{\text{gv}} \cdot e_{\text{gv}}} \times 100 \quad (\%) \quad (24)$$

3.3. Analysis procedure

The analysis procedure of the WB-SEG/PEM-FC combined system shown in Fig. 3 is described. The analysis procedure of each system of WB-SEG and PEM-FC shown in Figs. 1 and 2 is the same as that of the analysis method of the WB-SEG/PEM-FC combined system.

3.3.1. Energy flow and generation efficiency

First, the generating end output ($\dot{E}_{\text{sys},1}$ and $\dot{E}_{\text{sys},2}$) of WB-SEG and PEM-FC is determined. The molar flow rate and the amount of input-output of heat of each unit are calculable using the efficiency and the chemical reaction shown in Fig. 3(b). The energy flow of the system calculates and obtains

the energy balance in each unit using Eqs. (7)–(12). The whole energy balance is calculated by giving the amount of energy input-output in each unit to Eq. (13). The generation efficiency of the system is calculated by introducing into Eq. (14) the amount of fuel supply and the production of electricity taken from the energy balance.

3.3.2. Exergy flow and exergy efficiency

First, the fluid temperature in each unit outlet is calculated from the chemical reaction shown in Fig. 3(b), and the energy flow described in the section above. Next, chemical exergy (e_{ch}) and thermomechanical exergy (e_{tc}) of the entrance of each unit are calculated, and they give Eqs. (18)–(23). As a result, the exergy balance in each unit can be taken. When the exergy balance in each unit is decided, the exergy balance in the overall system will be given by giving this result to Eq. (17). The exergy efficiency of the system can calculate the exergy supply and the production of electricity of the fuel taken from the result of the exergy balance described above by giving Eq. (24).

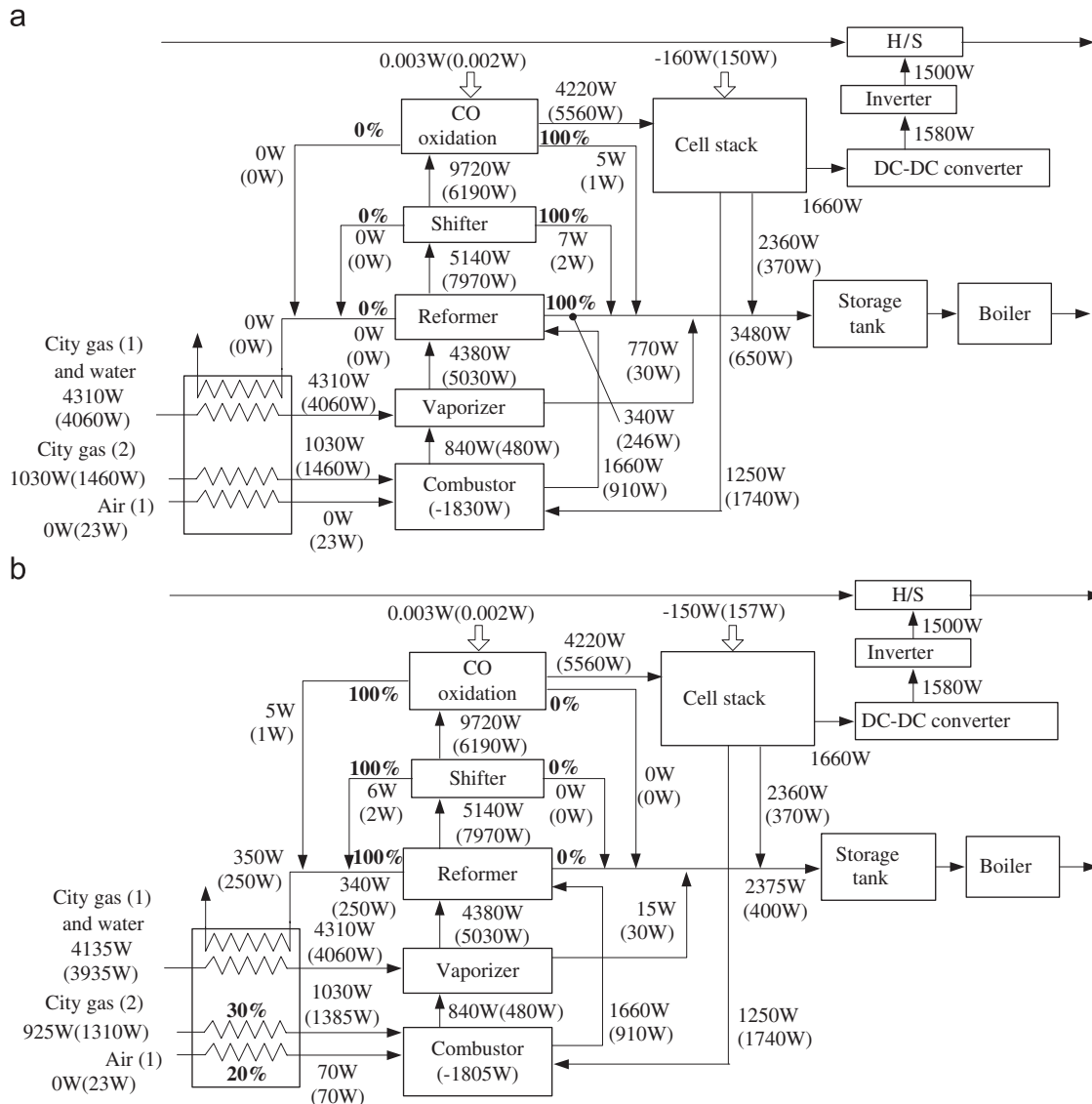


Fig. 5 – Energy flow and exergy flow of PEM-FC with reformer. (a) Fuel-preheating-less system. (b) Fuel-preheating system.

4. Analysis result

4.1. Energy balance and exergy flow

Figs. 4–6 show the analysis result of the energy and exergy flow of the WB-SEG, the PEM-FC, and the WB-SEG/PEM-FC combined system, respectively. The numbers in brackets in

these figures show exergy. Fig. (a) in each figure is the calculation result in the case of heating the fuel previously using the exhaust heat of the system. Each exhaust gas of the combustion gas of WB-SEG, the reformer unit of PEM-FC, shifter unit, and CO oxidation unit is used for preheating the fuel. The exhaust heat of the engine-cooling water of WB-SEG, the cell stack of PEM-FC, and the vaporizer unit is always supplied to the heat storage tank, and is supplied to

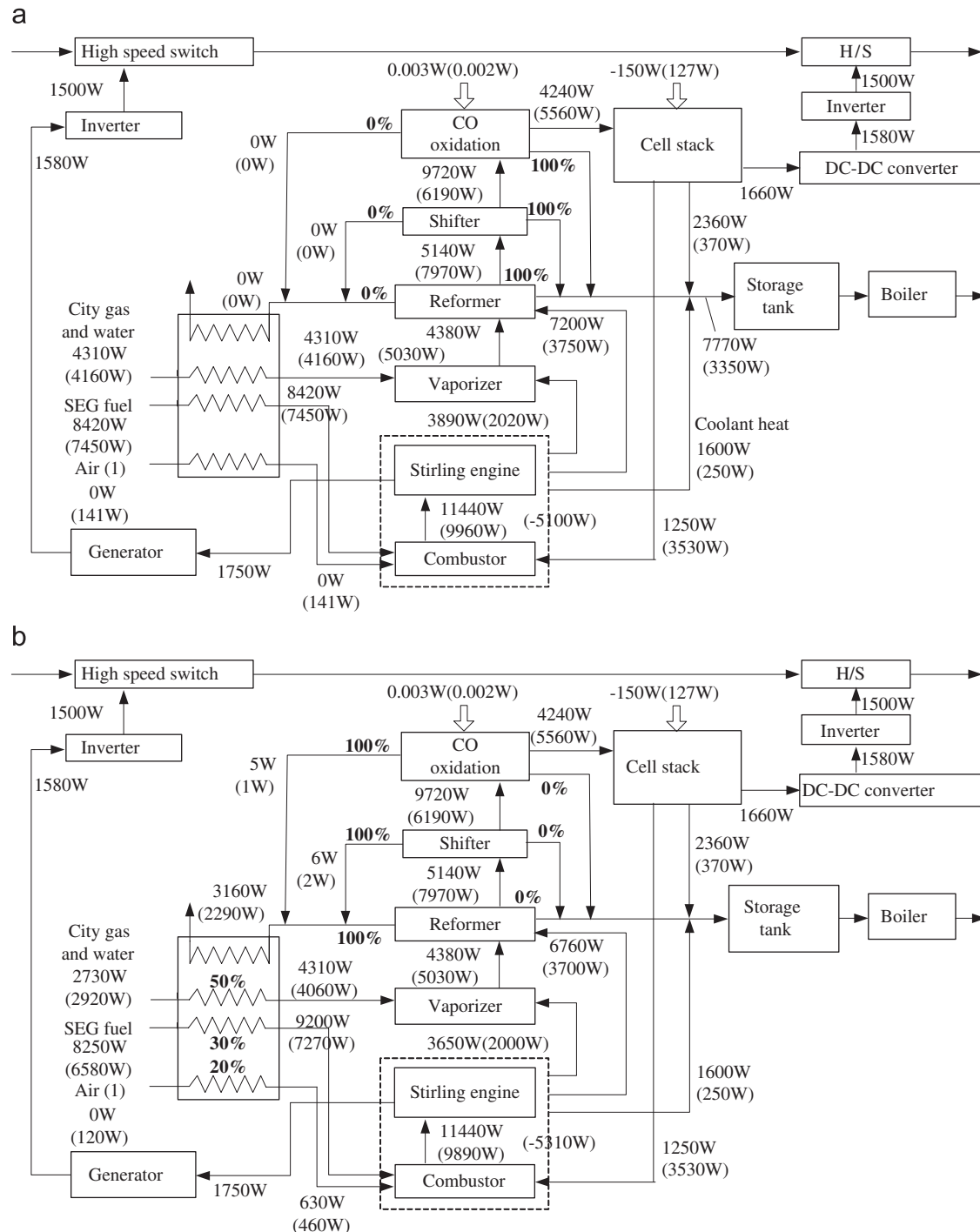


Fig. 6 – Energy flow and exergy flow of WB-SEG/PEM-FC combined system. (a) Fuel-preheating-less system. (b) Fuel-preheating system.

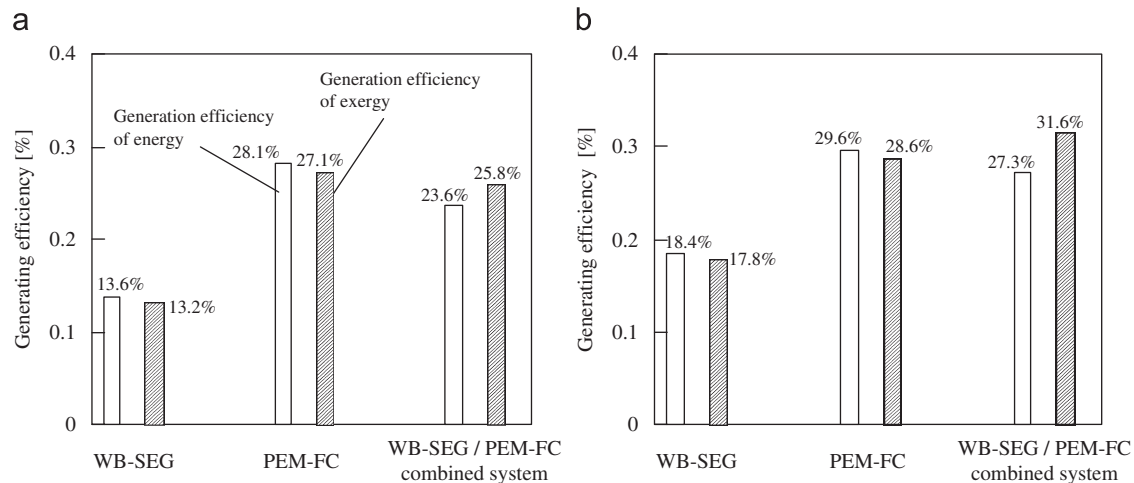


Fig. 7 – Analysis result of system generating efficiency. (a) Fuel-preheating-less system. (b) Fuel-preheating system.

the heat demand side. On the other hand, Fig. (b) in each figure is the calculation result in the case of storing all the exhaust heat of the system in the heat storage tank, without preheating the fuel.

(1) WB-SEG: As shown in Fig. 4(b), the exhaust heat of the exhaust gas system is given to preheating the woody biomass fuel and the combustion air at 50%, respectively. Exergy loss of the combustor and the Stirling engine is large in Figs. 4(a) and (b) (3440 and 3430 W). It is expected that the cause of this is the heat transmission characteristic of the high-temperature combustion gas in the combustor and the engine heat exchanger. The combustion gas of the woody biomass is considered to be exhausted without sufficiently exchanging heat for the engine heat exchanger. In order to reduce exergy loss of the system, the heat exchange quantity of combustion gas and the Stirling engine needs to be increased. The Stirling engine using woody biomass is attended by solid burning with difficult heat transmission control.

(2) PEM-FC: As shown in Fig. 5(b), 30% of the exhaust heat of the reformer unit, shifter unit, and CO oxidation unit is given to the city gas for burning. Twenty percent of heat of the exhaust gas is given to the air for burning. Moreover, 50% of exhaust heat is given to the city gas and water for reforming.

Exergy loss of the combustor of PEM-FC is 1805 W when heating the fuel previously. The exergy loss when not accompanied by preheating the fuel is 1830 W. These values are small compared with the combustor of WB-SEG described in Fig. 4. Moreover, exergy loss at the inlet and outlet of the shifter unit of PEM-FC is large. This is because the reformed gas of the reformer unit is supplied to the shifter unit after cooling. The reformed gas temperature of the reformer unit outlet is 800 °C (1073 K), and the reformed gas temperature of the shifter unit inlet is 180 °C (about 450 K). As one of the improvement means of exergy loss, it is feasible to smooth the difference in the reaction temperature in each unit. Accordingly, the rapid temperature change of reformed gas can be avoided. For example, development of a shift catalyst with high-temperature reaction is effective. On the other hand, development of a reforming catalyst with low-temperature reaction is also effective.

(3) WB-SEG/PEM-FC combined system: When previously heating the fuel for reforming, the fuel for burning (woody biomass), and combustion air of the WB-SEG/PEM-FC combined system, exhaust heat is distributed as shown in Fig. 6(b). This distribution ratio is the same as PEM-FC shown in Fig. 5(b). Exergy loss of the combustor as well as of WB-SEG shown in Fig. 4 is large. Exergy loss of the combined system with fuel preheating is 5310 W, and loss if there is no preheating is 5100 W. Exergy loss in front of and behind the shifter unit shown in Fig. 5 is also large.

4.2. Generation efficiency and exergy efficiency

Fig. 7 shows the analysis result of the generation efficiency based on energy and exergy. Fig. 7(a) shows the result in the case of supplying room-temperature fuel to the system. Fig. 7(b) shows the result of the system with preheating of the fuel. The energy generation efficiency of PEM-FC is the highest. Moreover, although the energy generation efficiency of the WB-SEG/PEM-FC combined system is lower than that of PEM-FC, it has improved more than that of WB-SEG. Energy generation efficiency and exergy generation efficiency will increase by all the systems, when a fuel is previously heated using exhaust heat. WB-SEG and the WB-SEG/PEM-FC combined system with fuel preheating improve energy efficiency and exergy efficiency greatly. This result is because the high-temperature exhaust heat of the combustor of the Stirling engine was used effectively. The energy generation efficiency of the WB-SEG/PEM-FC combined system with fuel preheating has improved greatly compared with WB-SEG. Moreover, the exergy efficiency of the WB-SEG/PEM-FC combined system exceeds that of PEM-FC. The WB-SEG/PEM-FC combined system realizes energy cascade utilization, and possible effective use of energy.

5. Conclusion

A combined system that uses the high-temperature exhaust heat of WB-SEG for city gas reforming and that supplies the

produced reformed gas to PEM-FC was proposed. The energy flow and exergy flow of this system were analyzed, and the following conclusions were obtained.

- (1) Exergy loss of the combustor of the WB-SEG is large, due to difference between the high-temperature combustion gas and the heat exchanger of the Stirling engine. In order to reduce exergy loss of the system, it is necessary to improve the heat-exchange characteristic described in the top.
- (2) The exergy loss in front of and behind the shifter unit of PEM-FC is large. This is because the reformed gas outputted from the reformer unit is cooled greatly. In order to improve exergy loss, the temperature change of each unit should be smoothed. For example, it is effective to develop a shift catalyst with high-temperature reaction and a reforming catalyst with low-temperature reaction.
- (3) Although the energy generation efficiency of the WB-SEG/PEM-FC combined system with preheating of the fuel is lower than that of PEM-FC, it is greatly improved compared with the WB-SEG system. Moreover, the exergy efficiency of the WB-SEG/PEM-FC combined system exceeds that of the PEM-FC system. Therefore, the proposed system in this paper can realize cascade use of energy, and can use energy effectively.

The following subjects are clarified in development of the PEM-FC and Stirling engine combined system.

- The dynamic characteristics of power quality and power supply [4].
- The environmental impact and economical efficiency of a Stirling engine when using biomass fuel [10].

In addition, the durability of the heat exchanger in the combustion gas of a Stirling engine, etc., is an issue.

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